# Measurement of the Equatorial Electrojet over India

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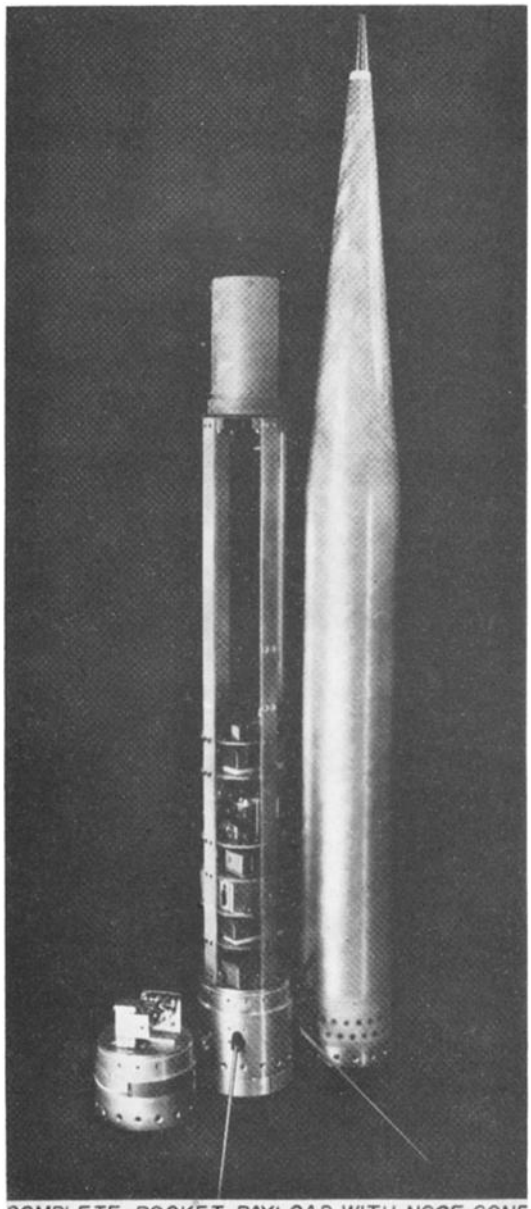
*Abstract.* To determine the vertical current distribution of the equatorial electrojet over India, four Nike-Apache sounding rockets were launched from near the magnetic dip equator at the Thumba Equatorial Rocket Launching Site (8.52°N; 76.87°E) near Trivandrum, India, during January 1964. A proton magnetometer measured the magnetic field, and a single dc Langmuir probe monitored electron density. UNH 64-4, launched at 1900 hours local time, showed no indication of distinct current on either the upward or the downward leg. UNH 64-1 and UNH 64-2 were launched in the morning near the peak intensity of the electrojet; UNH 64-3 was launched at 1630 hours in the afternoon. Results from these flights indicate that the equatorial electrojet over India is a thin layer of current, centered about 109 km, with a more diffuse tail extending up to about 130 km. A short distance from the center, as evidenced by the upward legs of the flights, the main current is thicker in vertical extent and lower in peak density. A second, weaker layer may exist near the center of the electrojet, centered between 140 and 145 km. Maximums of electron density were correlated with peak current densities, although the reverse case was not always evident. Small localized fluctuations in electron density were observed near the center of the electrojet. On UNH 64-3 the fluctuations had a periodic structure with a period constant in a time of 1.55 seconds.

## INTRODUCTION

The dynamo theory of ionospheric currents was long ago proposed to explain daily ($S_q$) variations in the earth's magnetic field [*Stewart*, 1882]. Two current loops (one in each hemisphere), fixed in relation to the sun, are proposed; daily magnetic variations at ground observatories result as the stations pass under the current system [*Chapman and Bartels*, 1940]. Currents in the northern loop flow counterclockwise, and those in the southern loop clockwise, contributing to a west-to-east current flow where they combine near the equator. The global ionospheric conductivity (depending on the magnetic field direction), collision frequencies, and the electron density, together with the global pattern of tidal winds, determine the resulting current density. The various components of the conductivity tensor have maximums in the $E$ region of the ionosphere between 100 and 150 km, making that the most probable region for finding the current. Stratification of the ionosphere restricts the currents to flow primarily in horizontal layers.

At the magnetic dip equator the earth's magnetic field is horizontal and generally northward. The electric field and principal current flow are horizontal and perpendicular to this; hence the Hall effect will produce a vertical potential. This can result in a space charge that effectively cancels the Hall voltage. The conductivity then approaches the direct conductivity along the magnetic field vector, and the current is enhanced in the narrow region where the magnetic field is nearly horizontal [*Baker and Martyn*, 1953]. This enhancement of the current about the magnetic dip equator is known as the equatorial electrojet [*Chapman*, 1951].

The horizontal distribution of current over the earth's surface can be deduced from ground measurements. The vertical distribution of the current density can be determined only by rocket measurements. Rocket measurements of the currents are made through precise determination of the magnetic field they produce [*Vestine et al.*, 1947; *Chapman*, 1954; *Cahill*, 1964]. The first direct measurement of ionospheric currents at the equator was made by *Singer, Maple, and Bowen* [1951]. Subsequent measurements near Jarvis Island in the Pacific indicated the possibility of a two-layer structure, the lower layer between 100 and 110 km and the upper layer above 120 km [*Cahill and Van Allen*, 1958; *Cahill*, 1959]. On these early flights the peak altitude of the rockets did not permit complete penetration of the current layers.



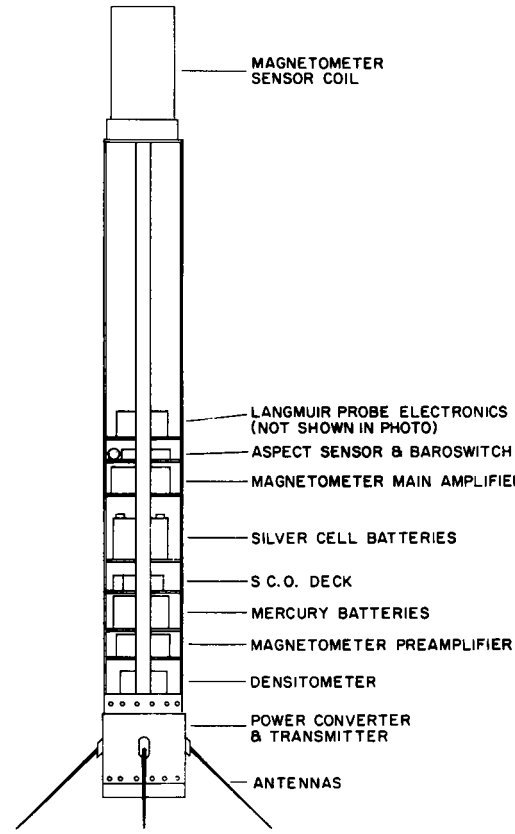




Fig. 1. Picture and layout diagram of the UNH rocket magnetometer payload showing the location of each major instrument.

The purpose of the flights reported here was to investigate the vertical current distribution of the electrojet over India to a greater altitude than had previously been achieved, and to correlate the magnetic profiles with simultaneous electron-density measurements.

## The Rocket Payloads

A nuclear free-precession magnetometer yielded a scalar measurement of the earth's magnetic field $|\mathbf{B}|$ in terms of the precession frequency $f$, and the gyromagnetic ratio, $\gamma$, of the proton [*Packard and Varian*, 1954].

$$|\mathbf{B}| = 2\pi f/\gamma$$

Measurements were made every 1.5 seconds during flight. After amplification the microvolt-level precession signal was applied directly to the FM telemetry and transmitted to the ground for recording. The frequency of the signal was later measured by comparing it with a 100-kc/s standard signal recorded on the same magnetic tape. Errors in the relative values of successive signals are due principally to noise on the signal. The magnetic field of the payload at the sensor location was kept below 3$\gamma$, after de-

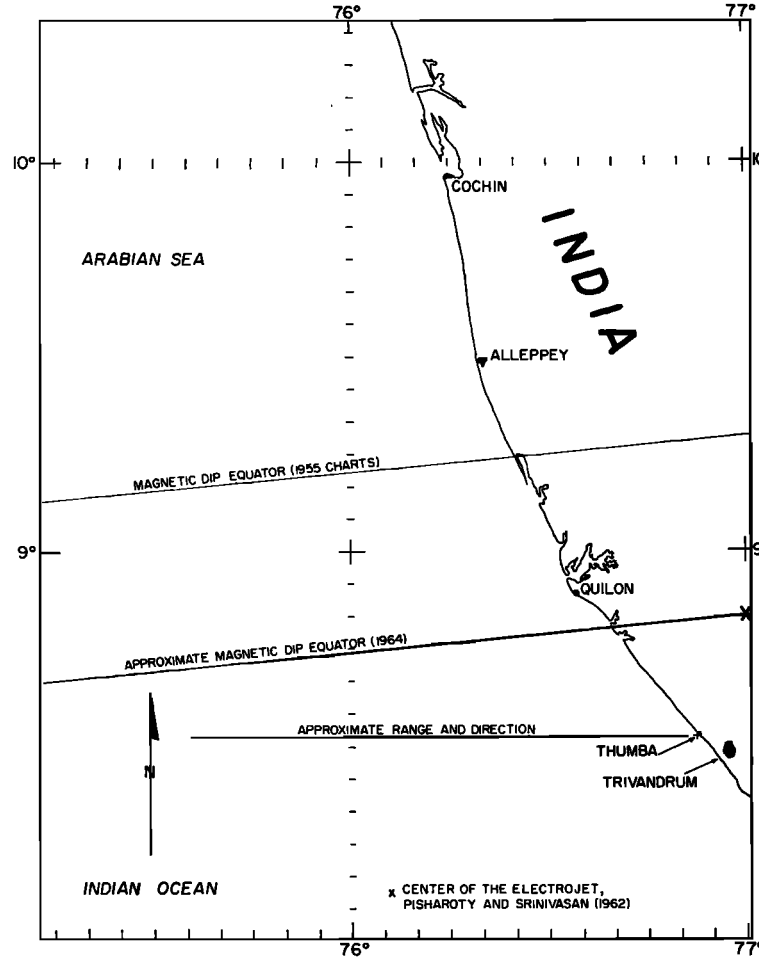



Fig. 2. Map of southern India, showing the launch location at Thumba, the approximate trajectory of the four flights, and approximate location of the center of the electrojet. The approximate magnetic dip equator was found by extrapolating the 1955 curve, using the approximate yearly shifts given on the 1955 charts. It is coincidental that the equator passes through the point given by Pisharoty and Srinivasan for the center of the electrojet.

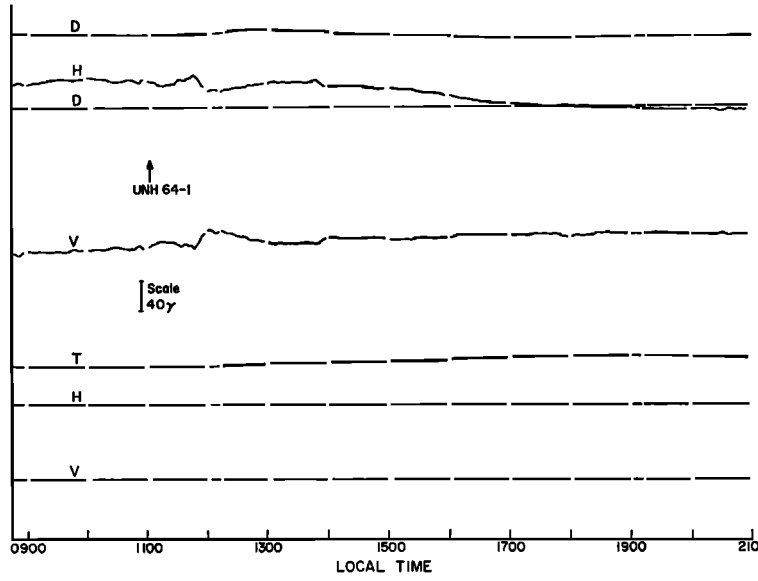



Fig. 3. Magnetogram from Trivandrum, India, of $H$, $D$, and $V$ variations between 0900 and 2100 hours local time on January 25, 1964. Time of launch of UNH 64-1 is indicated.

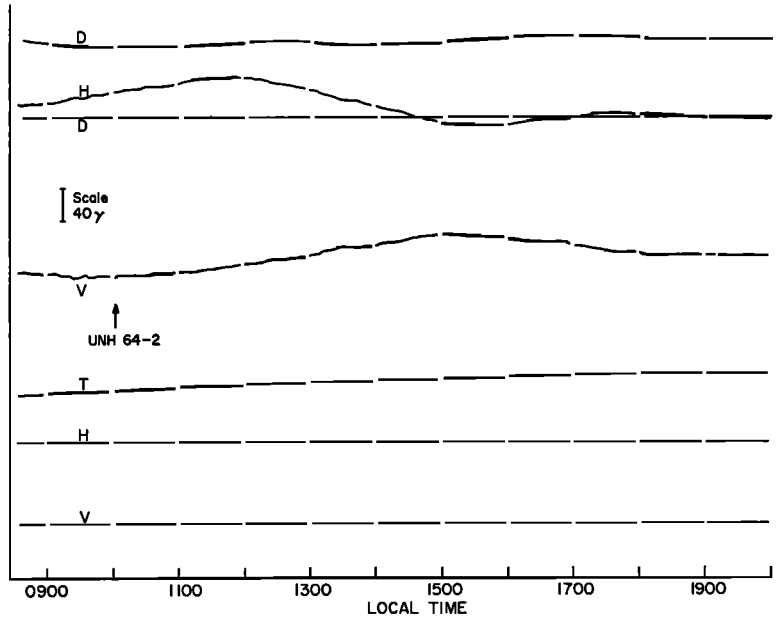



Fig. 4. Magnetogram from Trivandrum, India, between 0830 and 2000 hours local time on January 27, 1964. Time of launch of UNH 64-2 is indicated.

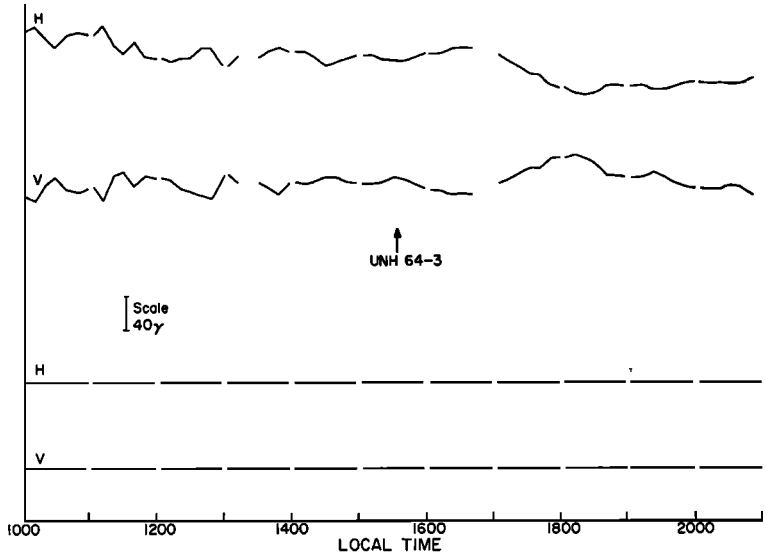



Fig. 5. Magnetogram from Trivandrum, India, of $H$ and $V$ variations between 1000 and 2100 hours local time on January 29, 1964. Time of launch of UNH 64-3 is indicated.

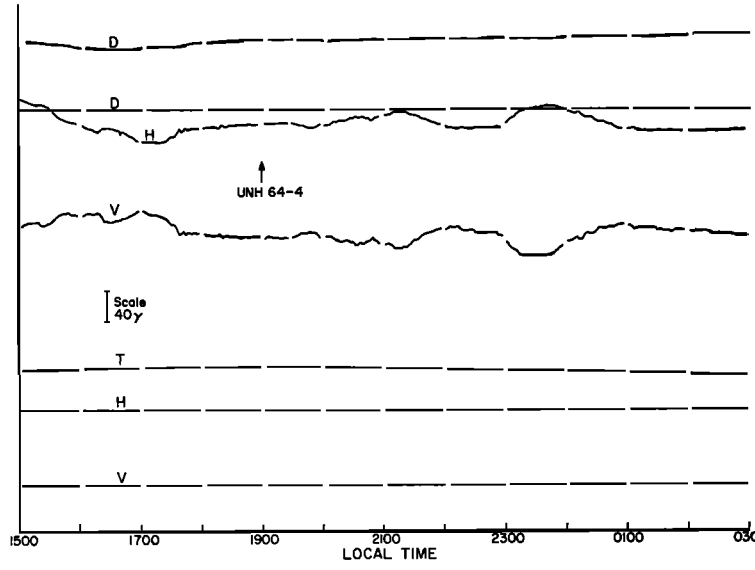



Fig. 6. Magnetogram from Trivandrum, India, of $H$, $D$, and $V$ variations between 1500 hours, January 31, 1964, and 0300 hours, February 1, 1964. Launch time of UNH 64-4 is indicated.

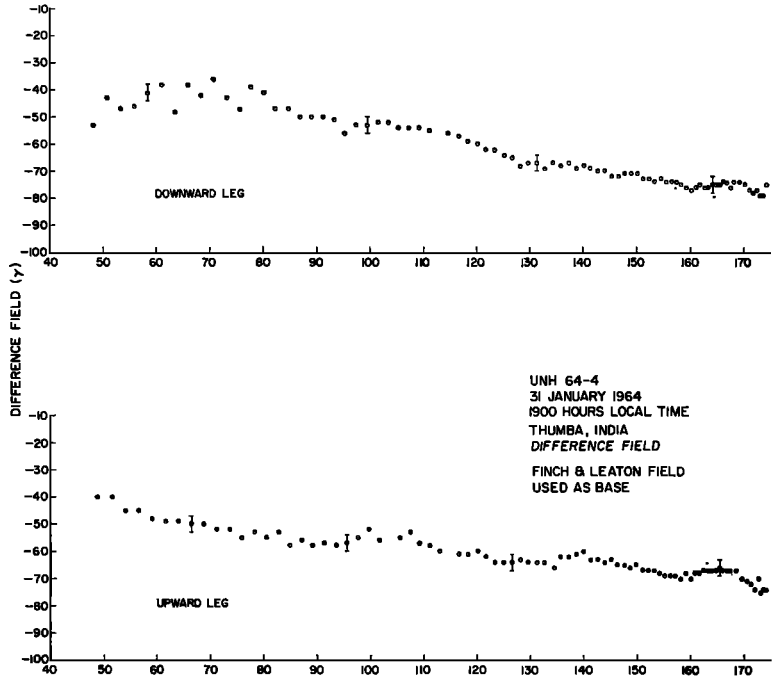



Fig. 7. The difference between the measured field and the calculated Finch and Leaton field in gammas, plotted against altitude in kilometers for UNH 64-4.

gaussing, to minimize errors introduced by the vehicle motion.

A simple dc Langmuir probe was used to monitor electron density. A constant 2.7-volt potential was applied between a tip probe and the payload base which was connected to the Apache motor. If electron temperature effects are neglected, the resulting probe current is proportional to the electron density [*Smith*, 1963]. The probe current was monitored at two levels of sensitivity by switching between two dc differential amplifiers, each covering an order of magnitude in current range.

An ionization chamber densitometer and a barometric pressure switch were flown for aid in trajectory determination. Rocket aspect information was obtained with a magnetic aspect sensor. A photograph and a drawing of the rocket payload, shown in Figure 1, depict the physical arrangement of the components.

## Flight Location

The rockets were launched from the Thumba Equatorial Rocket Launching Site near Trivandrum, Kerala State, India (8.52°N latitude; 76.87°E longitude). Measurements by *Pisharoty and Srinivasan* [1962] indicate that the center of the electrojet passes through the point 8.70°N latitude and 77°E longitude, about 0.2° north of the launch site. The magnetic dip equator crosses southern India from the southwest to northeast (Figure 2). All four rockets were fired at a corrected elevation (for wind) of 80° and a corrected azimuth of 270°. The approximate range of these flights was 75 nautical miles. Thus, the downward leg of each flight was closer than the upward leg to the center of the electrojet.

Two flights were launched close to the peak intensity of the electrojet: UNH 64-1 (Nasa 14.79 UE, Incospar 20.01) on January 25, 1964, at 1100 hours Indian Standard Time; and UNH 64-2 (Nasa 14.80 UE, Incospar 20.02) on January 27, 1964, at 1000 hours. UNH 64-3 (Nasa 14.81 UE, Incospar 20.03) was launched in the afternoon at 1530 hours on January 29, 1964, into slightly disturbed magnetic conditions (second 28-day recurrence of the December 2, 1963, storm). UNH 64-4 (Nasa 14.82 UE, Incospar 20.04) was launched in the evening at

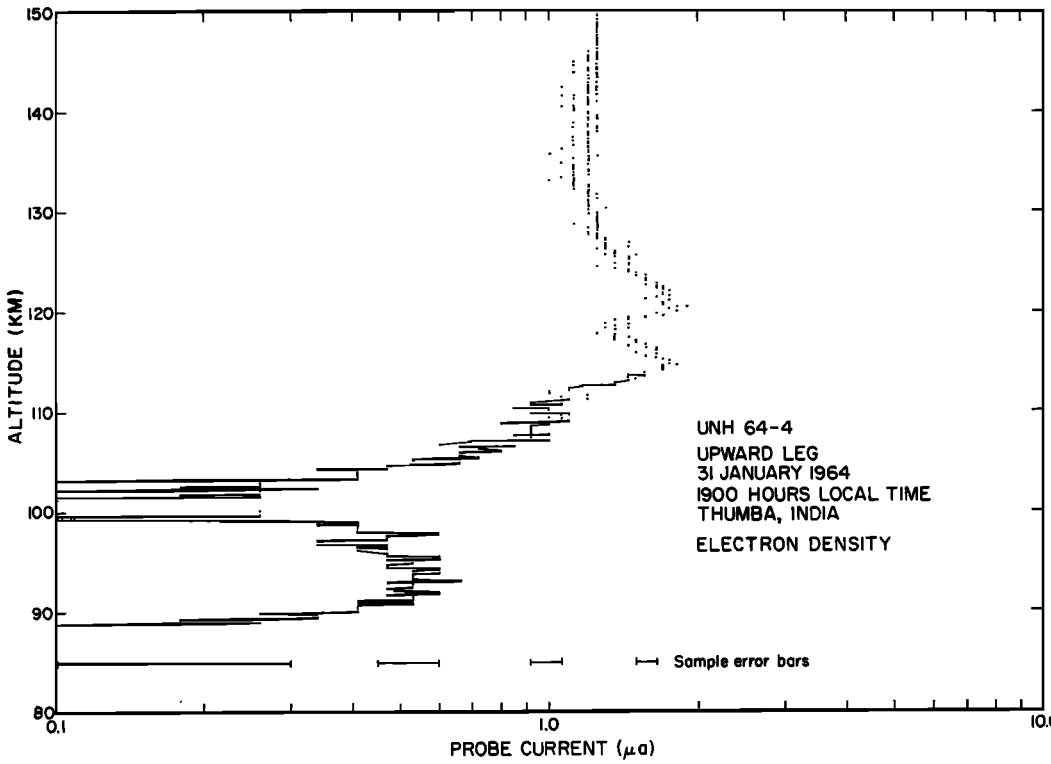



Fig. 8. Langmuir probe current (proportional to electron density) in microamperes as a function of altitude in kilometers for the upward leg of UNH 64-4.

1900 hours on January 31, 1964, to investigate the existence of nighttime currents.

Figures 3 through 6 are copies of preliminary magnetograms from the Trivandrum, India, Magnetic Observatory for the four launch dates (Subramanian, private communication 1964). The launch times are noted in the legends below the figures.

January 27 was one of five selected quiet days for the month. January 29 was active from the recurrence of the storm; January 31 was also active during the day but quieted down at the time of flight. $A_p$ indices for the flight days were 16 on the 25th; 4 on the 27th; 21 on the 29th; and 26 on the 31st.

### Description of the Flight Records

*UNH 64-4.* UNH 64-4 reached a peak altitude of 174 km. A reference magnetic field, calculated from the spherical harmonic analysis of *Finch and Leaton* [1957], was subtracted from the measured values of the field. The resulting difference field (Figure 7) showed no indication of distinct current on either the upward or the downward leg. If a diffuse layer of current existed between 100 and 170 km, it was too weak to produce a displacement of the magnetic field by as much as 10 $\gamma$.

The several fluctuations that appear on the flight record are approximately periodic in time. Their period is nearly the same as the rocket precession period for this flight, 39 seconds. These fluctuations may be due to rotation of the residual rocket and payload magnetic field, with respect to the geomagnetic field vector. The over-all nonzero slope of the difference field is interpreted as an indication that the Finch and Leaton reference field does not adequately describe the geomagnetic field in this region. On the assumption that ionospheric currents were negligible, the data from this flight were smoothed for use as a corrected reference field for the other three flights.

The Langmuir probe current between 95 and

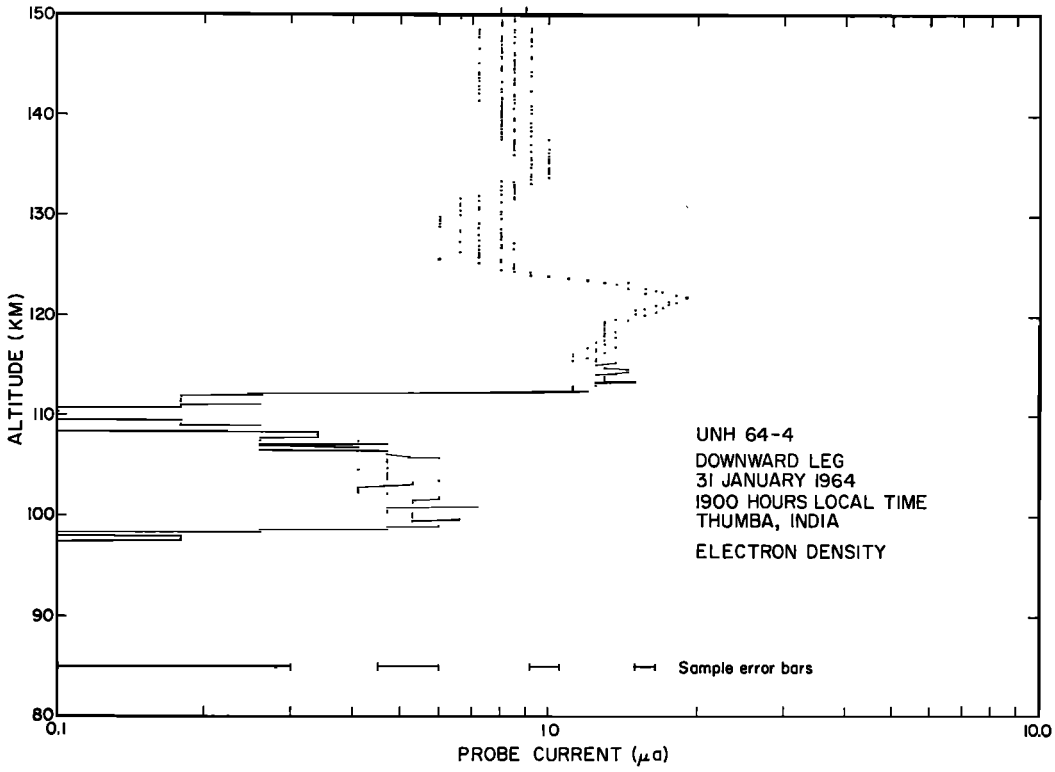



Fig. 9. Langmuir probe current (proportional to electron density) in microamperes as a function of altitude in kilometers for the downward leg of UNH 64-4.

150 km, proportional to the electron density, was less than that observed on the morning flights by a factor of 20 or greater, except for the local maximums at 115 and 122 km on the upward leg (Figure 8), and at 122 km on the downward leg (Figure 9), which were less by a factor of 15. The upward leg also had a local maximum between 90 and 100 km. On the downward leg the lower maximum had moved up to between 99 and 108 km. An inflection point corresponding to the upward maximums at 115 km was observed. The electron density above 125 km was less on the downward leg, and a small maximum appeared at 135 km on this leg.

*UNH 64-2.* Preliminary results from UNH 64-2 indicated a strong west-to-east current, 55 to 60 km down from apogee [*Maynard et al.*, 1965]. Using UNH 64-4 as the reference, a difference field was produced for detailed analysis of electric current evidence (Figure 10). The total field shift between 95 and 140 km was $68 \pm 4$ $\gamma$. This would produce a 34-$\gamma$ horizontal field contribution on the ground, on the assumption of a current layer of infinite extent. The actual departure of the horizontal component of the field from the nighttime value is (from Figure 4) 30 $\gamma$. Only two-thirds of this, 20 $\gamma$, is usually attributed to overhead currents, and the remainder to induced currents below the surface. The difference between ground-level field contribution as determined by rocket measurement, 34 $\gamma$, and that determined from surface measurements, 20 $\gamma$, should be explained. The overhead current, at least the electrojet ribbon, is not infinite in extent. The electrojet width has been estimated as greater than 300 km by *Cahill* [1959], and as 314 km by *Ogbuehi and Onwomechilli* [1964], from 1963 data over Africa. We estimate, for a ribbon 300 km wide, a reduction in magnetic field from 34 to 20 $\gamma$ at the earth's surface. Alternatively, induced subsurface currents may be less intense than elsewhere at this location, a boundary between land and

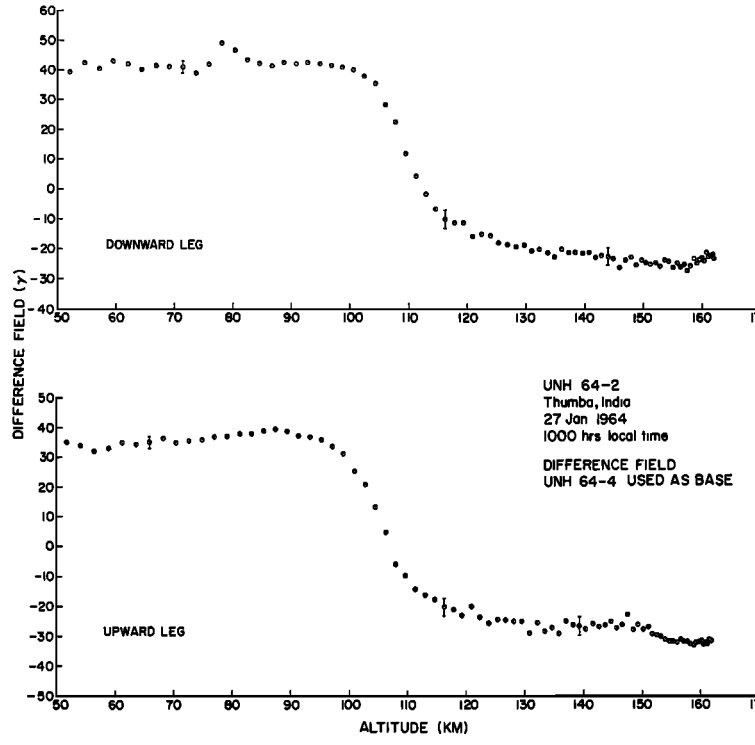



Fig. 10. The difference between the field measured by UNH 64-2 and that measured by UNH 64-4, in gammas, as a function of the altitude in kilometers.

sea, so that more than two-thirds of the 30 $\gamma$ is due to overhead current.

The slope of the difference curve is proportional to the current density (Figure 11). The current density plots are subject to the errors of the difference plots and to errors in drawing an average curve through the data points. These current densities should be taken as approximations to the actual currents. The main current layer was found to be centered at 105 km on the upward leg and 109 km on the downward leg; the discrepancy in altitude may be due to systematic errors in trajectory determinations. At 105 km, the estimated absolute error in trajectory is $\pm 3$ km and relative point-to-point errors are $\pm 0.1$ km. The current decreases gradually with increasing altitude to reach zero between 130 and 140 km. Indications of a second layer are present, centered about 152 km on the upward leg and 145 km on the downward leg. The smaller changes that suggest the second layer may well be due to time variation in the main layer. However, the presence of a field change at similar altitudes on both the up and down legs of the flight lends support to interpretation of the field changes as due to spatial structure.

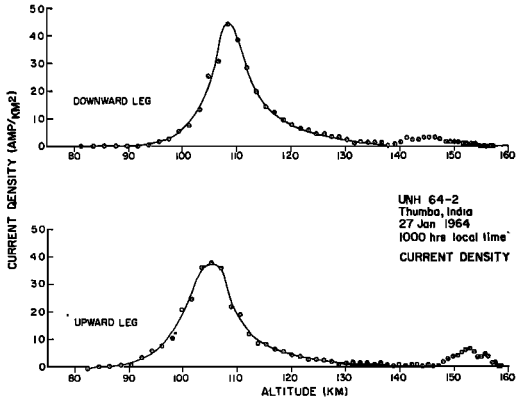



Fig. 11. The current density in amp/km² (derived from the slope of the difference curve in Figure 10), as a function of altitude in kilometers for UNH 64-2.

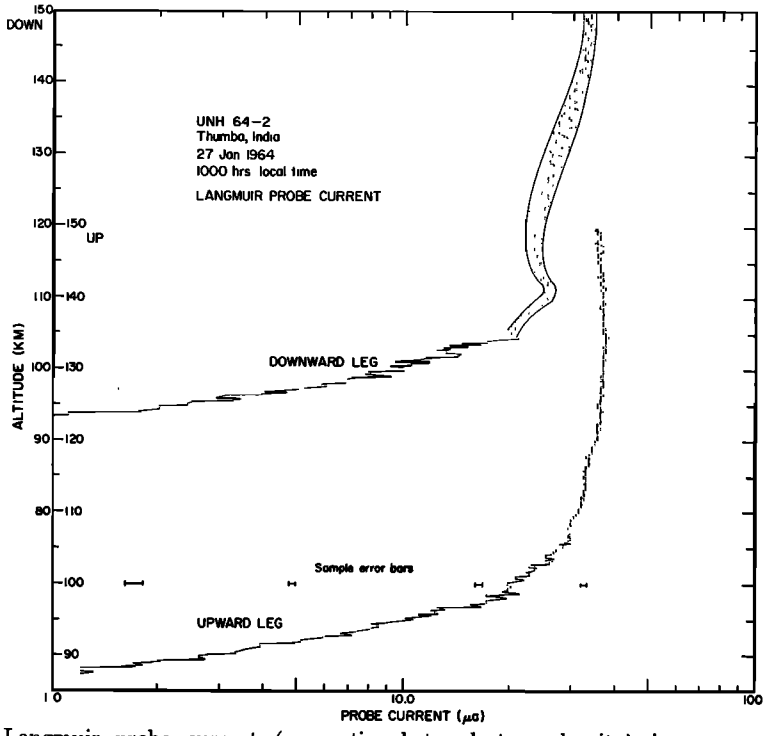



Fig. 12. Langmuir probe current (proportional to electron density) in gammas, plotted against altitude in kilometers for UNH 64-2. Note that there are two vertical scales.

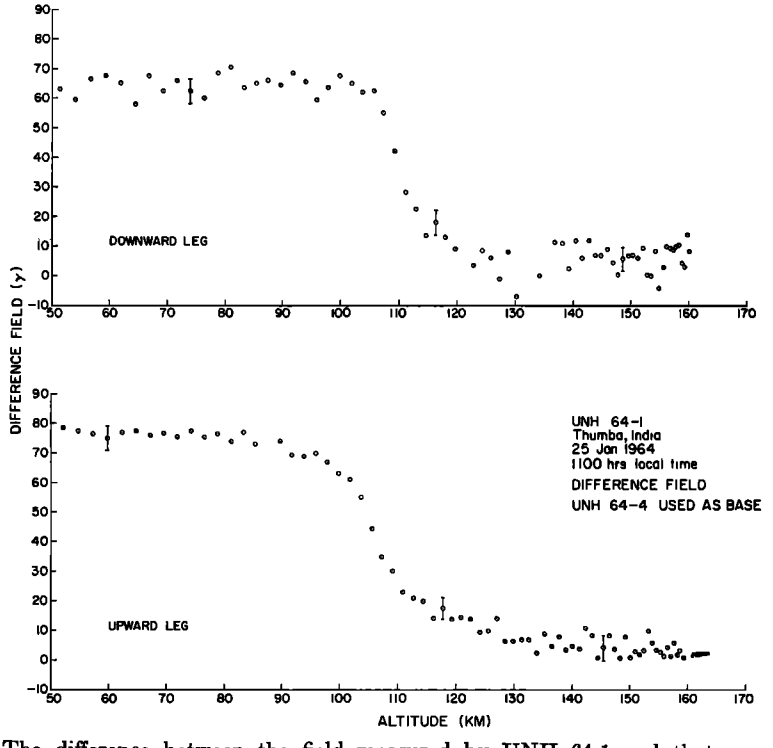



Fig. 13. The difference between the field measured by UNH 64-1 and that measured by UNH 64-4, in gammas, as a function of altitude in kilometers.

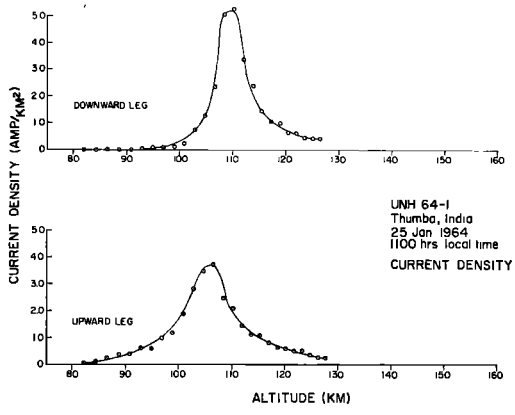



Fig. 14. The measured current density in amp/km² (derived from the slope of the difference curve in Figure 13), as a function of altitude in kilometers for UNH 64-1.

Langmuir probe current indicated the normal $E$-region increase in electron density between 90 and 100 km (Figure 12). On the downward leg a local increase about 110 km was observed at the same altitude as the main body of the current on that leg. The peak magnitude of the current (Figure 11), was correspondingly higher than on the upward leg. Measurements on the downward leg above 120 km showed a scatter greater than the expected error, indicating a possible fine structure in the electron density of the equatorial $E$ layer.

*UNH 64-1.* Reaching an apogee of 163 km, UNH 64-1 showed the peak in current at 106 km on the upward leg and 109 km on the downward leg (Figures 13 and 14). The current layer on the downward leg was again more intense and thinner in altitude. Both portions of the flight record exhibited diffuse current up to about 130 km; the bottom of the current layer decreased more abruptly. No attempt was made to estimate the current above 130 km, owing to scatter of the data. The total change in field on the upward leg was 70 ± 4 $\gamma$, accounting for a 35-$\gamma$ ground-level field contribution; and a (64 ± 4)-$\gamma$ contribution, accounting for 32 $\gamma$ on the ground, was seen on the downward leg. This is to be compared with the Trivandrum magnetogram departure from the night level of

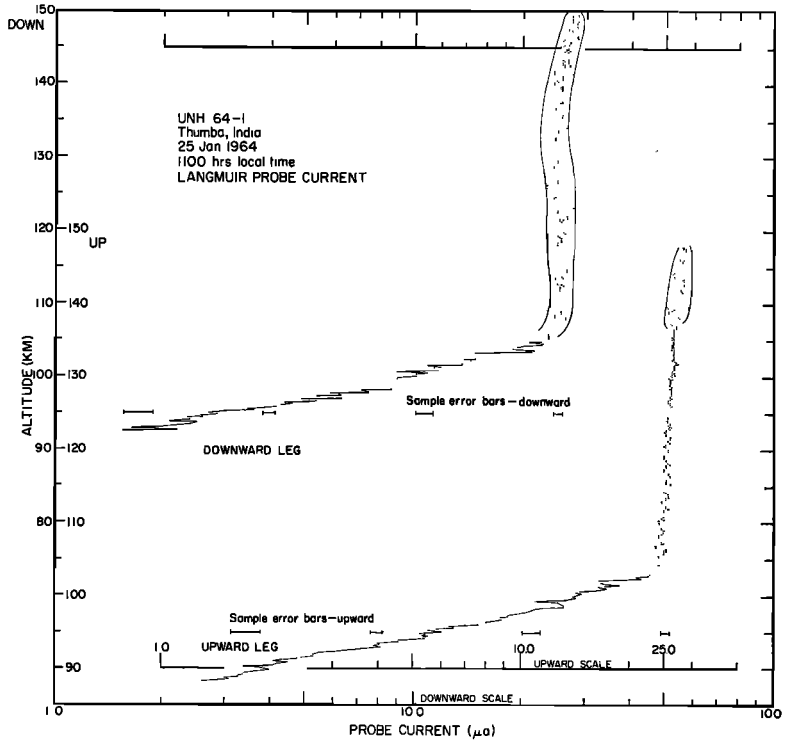



Fig. 15. UNH 64-1 Langmuir probe current (proportional to electron density) as a function of altitude in kilometers. Note that there are two vertical and two horizontal scales.

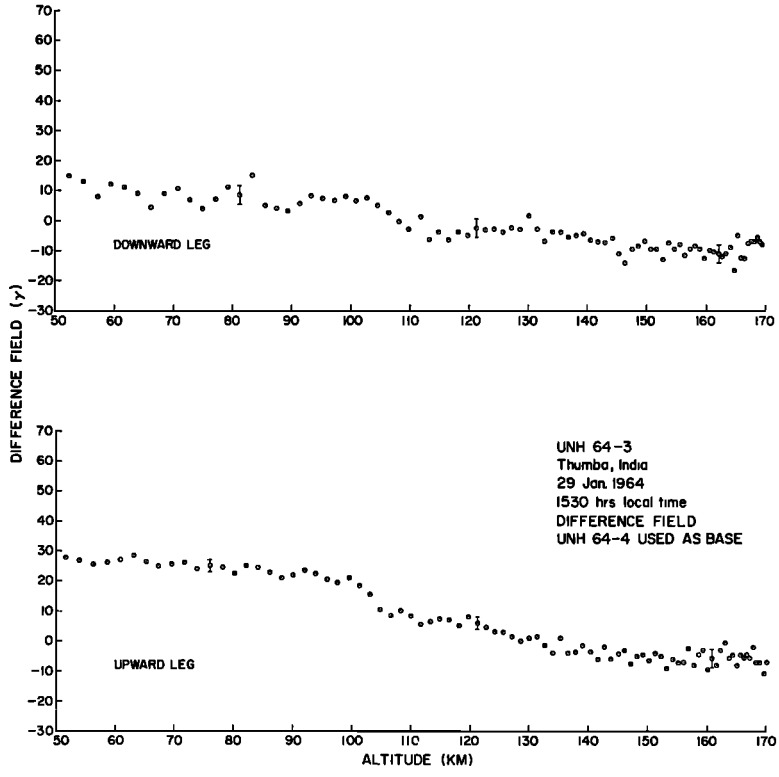



Fig. 16. The difference between the measured field and the UNH 64-4 measured field, in gammas, as a function of altitude in kilometers for UNH 64-3.

33 γ at the time of flight. The electron-density profile (Figure 15) exhibited the same scatter above 120 km on the downward leg that was observed on UNH 64-2. It was also present above 140 km on the upward leg. The period of rocket spin was about 0.2 second and the precession period about 50 seconds for UNH 64-1.

*UNH 64-3.* The record from UNH 64-3, flown in the afternoon, indicated two current layers on each leg (Figures 16 and 17). On the downward leg the lower current was centered at 107 km, and an upper layer was apparent at 140 km (corresponding to that of the downward leg on UNH 64-2). On the upward leg the center of the main current was at 103 km. A broad, diffuse layer appeared to be centered about 130 km. The lower current layers were reduced in magnitude by a factor of about 4, from the morning flights, as was the electron density. The magnitude of the upper layers for flight 64-3 appears greater than those of flight 64-2, although the electron density is lower by a factor of 4.

The upward-leg electron-density profile (Figure 18) has a maximum near 105 km and a gradual increase near 130 km, close to the peaks in current density. The downward-leg profile

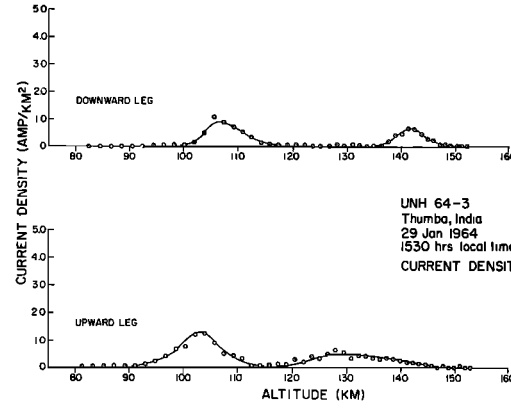



Fig. 17. UNH 64-3 current density in amp/km² (derived from the slope of the difference curve in Figure 16), plotted against altitude in kilometers.

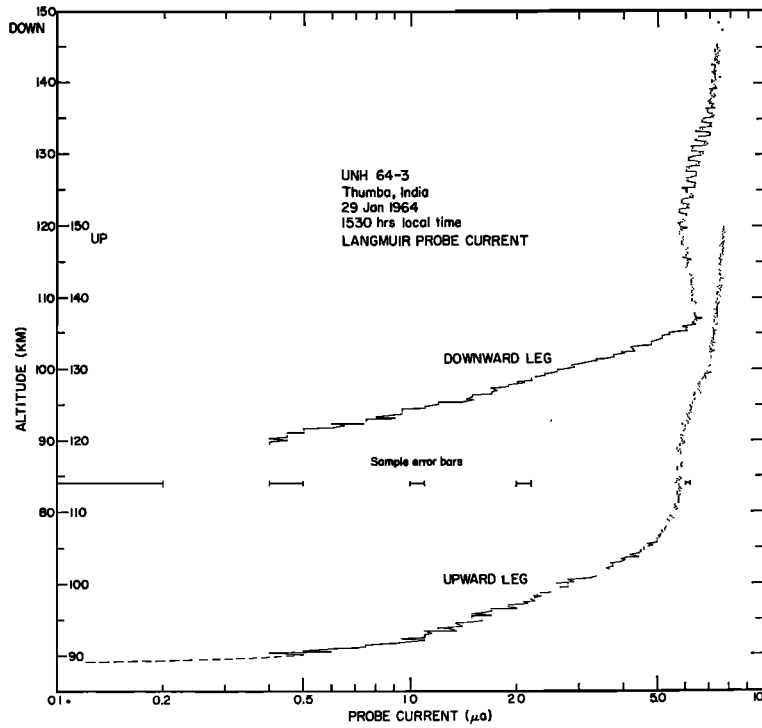



Fig. 18. UNH 64-3 Langmuir probe current (proportional to electron density) as a function of altitude in kilometers. Note that there are two vertical scales.

has a maximum centered about 103 km and a distinct oscillatory variation superimposed on a gradual increase between 120 and 140 km. The fluctuations are of the order of 8 to 10% of the total electron density and have approximately a constant period of 1.55 seconds. The spin period for this flight was approximately 0.3 second, and the precession period approximately 67 seconds.

Full moon was on January 27, 1964; thus, UNH 64-3 was fired into the time of maximum negative effect ($L$ current opposed to $S_q$ current) of the lunar current system ($L$) [*Chapman and Bartels,* 1940]. No negative departure was evident on the magnetogram, probably owing somewhat to disturbed magnetic conditions. All the currents deduced from rocket observations were flowing west to east.

## Conclusions

The results from these flights indicate that the equatorial electrojet over India is an intense, thin layer of current centered about 109 km, with a more diffuse tail extending up to about 130 km. A short distance away from the dip equator, as evidenced by the upward leg of these flights, the current appears thicker in vertical extent, lower in peak current density. The diffuse tail remains up to about 130 km. Near the center of the electrojet there may exist a second current layer about 10 km in vertical thickness and centered at 140 to 145 km. Careful examination of the flight records of UNH 64-2 and UNH 64-3 leads us to believe that there are weak currents at these altitudes.

It is possible that time variations in the magnetic field, more apparent in flight records near apogee where the rocket is moving relatively slowly, have caused the magnetic changes that appear to be currents. The height fluctuation of the second layer observed on the upward legs may be a function of the magnetic activity. The discrepancy between rocket and ground determination of the contribution by the electrojet to horizontal magnetic field may be due to the finite width of the electrojet resulting in con-

siderable reduction in field contribution at ground level, or perhaps to an anomalously low induced current contribution.

No thin layers of high electron density associated with sporadic $E$ were observed on the three daytime flights. Maximums of electron density correlated with peak current density, although the reverse was not always evident. Ground ionosonde indications of sporadic $E$ at 120 km may have been reflections from the current sheets [*Bowles and Cohen,* 1962]. Near the center of the electrojet, very localized, small fluctuations in electron density were indicated, possibly a condition of turbulence of the plasma. On UNH 64-3, the fluctuations had a periodic structure with an apparent period of 1.55 seconds and an apparent vertical thickness of 1.4 km.

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